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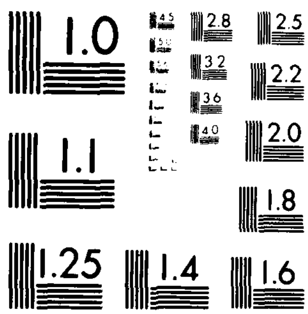

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One of the primary considerations in all types of spraying operations is where the dispensed material will impact on the ground. This impact area is determined by the trajectory of the liquid drop which can be predicted if the drag is known. Each drop, depending upon its size and physical properties, will have a slightly differing drag and consequently, trajectory. Thus, a reliable calculation of an impact area can only be done if the effects of appropriate physical properties upon the drag are known. The experiment reported herein was designed to provide

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20. ABSTRACT CONTINUED

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DESERT RESEARCH INSTITUTE
UNIVERSITY OF NEVADA SYSTEM

AN EXPERIMENTAL DETERMINATION OF THE DRAG ON LIQUID DROPS

Final Report

Contract Number DAAG 29-77-G-0172

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NOTIFICATION

Sections of this report in entirety or part have been edited and submitted as a paper for publication to the Journal of Fluid Mechanics.

Further refinement of the results are in progress and will be submitted for publication in the future.

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FINAL REPORT

I. INTRODUCTION

One of the primary considerations in all types of spraying operations is where the dispensed material will impact on the ground. This impact area is determined by the trajectory of the liquid drop which can be predicted if the drag is known. Each drop, depending upon its size and physical properties, will have a slightly differing drag and consequently, trajectory. Thus, a reliable calculation of an impact area can only be done if the effects of appropriate physical properties upon the drag are known.

The experiment reported herein was designed to provide the needed understanding of the effects of physical proerties upon the drag of liquid drops. The fall velocity, from which the drag can be calculated, was measured for five different liquids of varying viscosity and surface tension. In addition, one of the liquids was thickened in order to change the viscosity, while not affecting the surface tension, thus isolating the effect of viscosity on drag. Thickening was accomplished with two different thickeners, one of which produced non-Newtonian properties. Thus, any differences in the rheological properties of Newtonian and non-Newtonian liquids were tested. With the viscosity effects isolated, the effect of surface tension alone was then determined.

II. BACKGROUND

A sphere falling in a fluid medium will attain a constant or terminal velocity. When falling at terminal velocity, all of the forces on the sphere are in equilibrium. If the sphere is of a non-deformable material, this equilibrium is the balance between the weight, buoyancy, and the aerodynamic drag forces on the sphere. If however, the sphere is a liquid drop, the balance can become more complicated. The other forces that can arise are due to deformation of the drop. In that case, the balance of forces is different. Surface tension, the hydrostatic pressure change within the drop, internal circulation, along with the aerodynamic pressure, will control the shape of the drop as it falls.

It has been known for some time that large raindrops are deformed from a spherical shape as they fall. The deformation shape is one of a flattened bottom with a smoothly rounded upper surface. For raindrops, the degree of deformation is dependent on the size of the drop.

Several authors have considered how the water drop is deformed while falling. McDonald (1954) in a paper based on the previous works of Lenard (1904) and Spilhaus (1948), determined that the significant forces controlling the shape were the external aerodynamic pressure, the surface tension and the hydrostatic pressure gradient in the drop. He neglected internal circulation and electric charge. By using pictures of drops taken by Magono (1954), he deduced the external pressure from the drop shape. The integrated pressure was then found to be in reasonable agreement with the drop weight.

Pruppacher and Beard (1970) found, experimentally in a wind tunnel, that for water drops with radii $< 140\ \mu m$, there was a slight deformation toward an oblate spheroid and with radii between 500 and 4500 μm, the deformation parameter $(\frac{a}{b})$ was linearly related to the equivalent spherical radius.

Pruppacher and Pitter (1971), in a paper which refines the work of Savic (1953), criticize the neglect of internal circulations for drops with radii > 2.5 mm but find the assumption valid for drops smaller than 2.5 mm radius. They developed a semi-empirical model which predicts the shape of water drops with radii between 170um and 4.0 mm. The shapes are in agreement with experimental results.

LeClair, et al (1972) compare several theoretical approaches with experimental evidence to determine the internal circulation of a water drop falling at terminal velocity. They conclude that the effect is small for drops that remain almost spherical.

Green (1976) shows that the drop distortion parameter, a/b, the minor to major axis ratio, can be calculated with excellent approximation by considering only a balance between hydrostatic and surface tension forces at the drop equator. The aerodynamic pressure distribution creates the flattened and concave bottom side of drops.

The size of the drops that actually deform is large compared to the size range usually studied in drop fluid dynamics. Theoretical approaches have not been able to calculate adequately the terminal velocity or the drag coefficient. The only results that have been obtained for most drop sizes are experimental. These results have varied significantly. The experiment covering the widest range of drop size was done by Gunn and Kinzer (1949). They made measurements of the terminal velocity of drops between 0.01 and 0.53 cm in diameter. The environment was maintained at 50% relative humidity. Drop evaporation may have influenced the results. In addition, the purity of the water used in the experiments was not controlled.

Beard and Pruppacher (1969) measured the terminal velocity of small drops falling in saturated air with the use of a wind tunnel. They investigated the size range from 10 to 450 μm in radius. Their results were similar to those of Pruppacher and Steinberger (1968) who used solid spheres. LeClair, et al (1970) numerically integrated the steady state Navier-Stokes equations to determine the drag on a sphere falling at terminal velocity. They obtained results that agreed with the experiments of Pruppacher and Steinberger and of Beard and Pruppacher.

The effect which a change in the physical properties of a drop would have on the drag has received only cursory investigation. A substance with a surface tension different from water would behave differently at terminal velocity provided it deforms. Buzzard and Nedderman (1967) experimentally determined the drag coefficient for various types of liquid drops falling in air. Experimental data was obtained both before and after terminal velocity was reached. They investigated a drop size range from 1.8 to 9.3 mm diameter. There is a large degree of scatter in their results.

They found that high viscosity liquids at high Reynolds number[1] had a steady decrease of drag coefficeint with increasing surface tension. Low viscosity fluids had no apparent dependence on surface tension but the drag coefficient was lower than for the high viscosity ones. This result may relate to internal circulations. Distilled water acted as a low viscosity fluid; conversely, contaminated water acted as a high viscosity fluid. The range in surface tension of the liquids studies was not large.

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[1] The Reynolds number is defined as:

$Re = 2a\, V/\eta$ where a is the drop radius, V is its velocity, and η is the kinematic viscosity.

III. THEORY

The measurements reported in this paper are presented in the form of data relating the coefficient of drag (C_D) to the Reynolds number (Re). Both of these quantities are derived from the actual parameters measured, fall velocity and drop mass. Therefore, it is appropriate to give a brief discussion describing the calculation of C_D and Re from the fall velocity and drop mass.

The resisting force exerted by a medium on a body passing through it is called the drag. Normally, the drag cannot be measured directly and, in fact, neither the shape nor pressure distribution are known quantities for deformable liquid drops. By physical reasoning the drag force (D) can be related to the dynamic pressure by

$$D = C_D \; 1/2 \; \rho_a V^2 \pi r^2 \tag{1}$$

where C_D, the drag coefficient, is a dimensionless parameter which is determined experimentally, V is the fall velocity, ρ_a the air density, and r is the drop radius. For falling liquid drops, C_D can be calculated by measuring the fall velocity provided that the drop mass is known. In that instance, the analysis is as follows:

At terminal velocity, the drag will be balanced by gravity

$$D = mg = \frac{4}{3}\pi r^3 (\rho_\ell - \rho_a) g \tag{2}$$

where ρ_ℓ is the drop liquid density and m the drop mass. From equations (1) and (2) C_D becomes

$$C_D = \frac{8}{3} \left(\frac{\rho_\ell}{\rho_a} - 1\right) \frac{gr}{V_T^2} . \tag{3}$$

The drop radius can be obtained by weighing the drop and calculating the equivalent spherical radius

$$r = \left(\frac{3m}{4\pi\rho_\ell}\right)^{1/3}$$

which is used in (3) even though the drop may be deformed from spherical.

The drag is intimately related to the flow pattern about the drop. When the Navier-Stokes equation for viscous incompressible flow is non-dimensionalized, the dimensionless parameter governing the nature of the flow pattern (laminar or turbulent) is formed. This is the Reynolds number, Re. Re is the ratio ofthe dynamic pressure (inertial force) to the shearing stress (viscous force),

$$Re = \frac{2r\rho_a V}{\mu_a} = \frac{\rho_a V^2}{\left(\frac{\mu_a V}{2r}\right)} \tag{4}$$

where μ_a is the viscosity of air. By suitable rearrangement of variables in equation (3), a relation between C_D and Re can be obtained as

$$V_T = \frac{16}{3} g(\rho_\ell - \rho_a) \frac{r^2}{\mu_a} \frac{1}{C_D Re} \tag{5}$$

Thus, the relation of C_D versus Re forms a unique combination which determines the fall velocity of a drop. Drag measurements are usually presented showing values of C_D versus Re for this reason among others. One can also show from dimensional analysis that

$$f\left(\frac{2rV_{\rho_1}}{\mu_a}, \frac{8\ D_{\rho_\ell}}{4\pi r^2 V^2{}_{\mu_a}}\right) = f(Re, C_D) = 0. \tag{6}$$

A liquid drop, unlike a solid sphere, can develop an internal circulation within it due to the shearing stress at the liquid-gas interface. This internal

circulation can affect the drag significantly if of sufficient degree. The drag coefficients reported in this paper shed considerable light on the functional role and quantitative effect of internal circulation upon the drag. The internal circulation itself is not evaluated but is related to drag via the ratio of the drop's fluid viscosity to that of air. This ratio determines the efficiency at which momentum is transported across the liquid-interface. Some theoretical evaluations have been performed and can now be discussed.

The drag coefficient is composed of two components, frictional (C_{DF}) and pressure (C_{DP}), which are given by LeClair (1970) as

$$C_{DF} = \frac{8}{Re} \int_0^{\pi} [(\frac{\partial v}{\partial r} - \frac{v}{r}) \sin\theta - \frac{\partial u}{\partial r} \cos\theta] \sin\theta d\theta \tag{7a}$$

$$C_{DP} = \int_0^{\pi} p(r=a,\theta) \sin 2\theta d\theta, \tag{7b}$$

where u is the radial velocity, v the tangential velocity of the flow field, and $C_D = C_{DF} + C_{DP}$.

LeClair (1972) has numerically evaluated these expressions for water drops of Re $\leq$ 400. The hope of evaluting the expressions for higher Re is quite dim owing to the complexity of interactions amongst several factors. The above expressions require a knowledge of the external aerodynamic pressure distribution as well as the internal circulation pattern. For a non-circulating drop the aerodynamic pressure will be determined by shape and Re alone, but when internal circulation is in effect it alters not only the friction drag by decreasing the velocity shear at drop surface but also the pressure drag by retarding the separation of the boundary layer. Fortunately, it appears (Savic, 1950; McDonald, 1954; Pruppacher and Pitter, 1971; Green, 1975) that internal circulation generally has little effect on drop shape.

Mathematical expression for relating internal circulation to drag for Stokes flow of a liquid sphere has been found by Hadamard (1911) and Rybczinski (1911) as

$$C_D = C_{DS} \left(\frac{1 + 2/3 \frac{\mu_a}{\mu}}{1 + \frac{\mu_a}{\mu}} \right)$$

$$C_D \sim C_{DS} \left(1 - \frac{1}{3} \frac{\mu_a}{\mu}\right) : \frac{\mu_a}{\mu} << 1 \qquad (8)$$

where C_{DS} is the Stokes drag coefficient.

The expression shows the internal circulation to affect the Stokes drag <1%. No relation exists for higher Re. The measurements reported herein permit the derivation of an expression for higher Re.

IV. EXPERIMENTAL IMPLEMENTATION AND PROCEDURE

Excellent accuracy is required if any useful information on the subtle effects of viscosity and surface tension is to be achieved. Previous work in this lab (Eaton and Hoffer, 1976) developed such a measurement technique of high resolution, accuracy, and reproducibility. The present experimental setup is a further refinement of this technique. Basically the technique measures the fall velocity by determining the time to traverse consecutive light beams.

The experimental technique can be divided for purposes of discussion into apparatus and procedure, which in turn can be subdivided into descriptions of (1) the fall column, (2) drop generation technique, (3) drop mass measurement, and (4) drop detection and time of fall. The experimental equipment and procedure will be described in the following sections.

A. FALL COLUMN

The basic element of the experiment, depicted in Figure 1, is the fall column through which the drops will fall. It is constructed of several sections of a six inch inner diameter PVC (polyvinylchloride) pipe. The column extends through three floors of the Atmospheric Sciences Center building giving a total usable fall distance of 11.36 meters. The column is sealed at the top by the drop generation box enclosure and at the bottom by an end cap on the pipe. A good seal was required because of a definite pressure differential between the first and third floors caused by the building's air conditioning system. The seal minimized any organized air circulation in the column to a level below that detectable by a Thermo-Systems, Inc. constant temperature anemometer (<1 cm/sec).

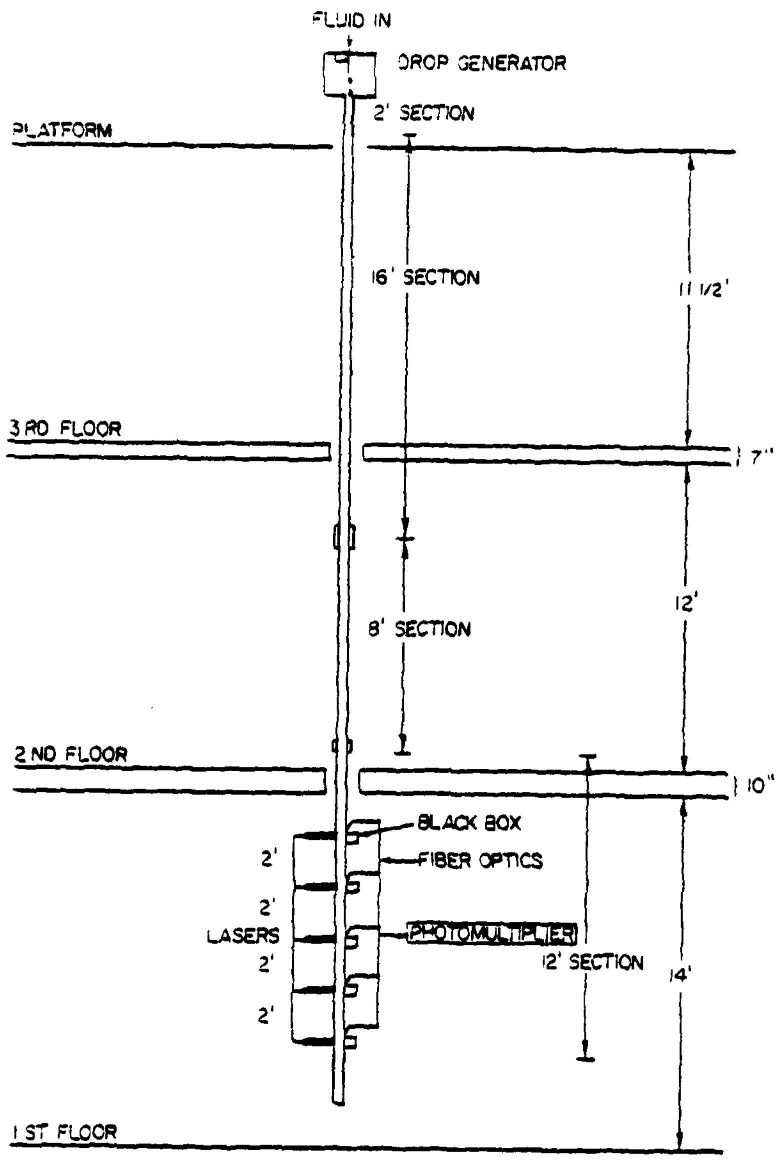

Figure 1: Schematic of Fall Column

Problems were encountered (see section D, Drop Detection) that indicated turbulence within the column. Holes were drilled at various levels of each floor for temperature probes and indeed it was found that the building's air conditioning system kept the third floor several degrees cooler than the first. The initial attempt to solve this hydrostatic stability problem was to wrap heating tape around the column on the third floor. However, due to the difficulty of controlling the degree of heating this method of temperature control was abandoned. The problem was solved by enclosing the first and second floors within a wood framework housing walled with polyethylene sheeting. This enclosure was then temperature controlled by placing an air cooler on the first floor and a fan at the roof of the second floor. The fan sucked air up from the air cooler thus ventilating the first and second floors with cool air. These measures isolated the column from the building's air conditioning system and insured hydrostatic stability within the column. A glass window view port was inserted five feet above the third floor which allowed the observation of smoke injected into the column. The observed behavior of the smoke confirmed hydrostatic stability within the column.

The drop generator enclosure at the top of the column mounts on a micrometer stage which itself is fastened to the third floor roof. The enclosure is connected to the column pipe through flexible neoprene tubing. By adjusting the micrometer, drops could be positioned to fall within ± 1 mm of the center of the column.

B. DROP GENERATION

A drop generation technique which follows that of Sweet (1965) and used previously in this laboratory (Eaton and Hoffer, 1970) was used intially to generate drops. This technique allows for the creation of uniform size drops from a

cylindrical jet issuing from small diameter capillary tubing by forcibly imposing a sinusoidal pressure disturbance on the jet. The pressure disturbance grows exponentially and thus the jet breaks up into uniform drops determined by the frequency, capillary diameter, and jet pressure. The size can be increased by decreasing the frequency, increasing capillary diameter or increasing jet pressure. The size can be predicted theoretically from the works of Rayleigh (1945), Sweet (1965), and Lindblad and Schneider (1965). The reader is referred to the aforementioned references for an explanation of how single drops are separated out from the uniform stream of drops.

This technique of drop generation worked extremely well for the production of drops with Reynolds number 100-200 (800-1,000 μm diameter) and it was hoped it could be extended to larger sizes. To increase the size of drops, increasingly larger diameter tubing was used which required higher pressure. The pressure was provided by a compressed air tank and regulated by a Brooks Instruments regulator. Typically a pressure of >40 psi was required for high viscosity liquids ($\mu > 20$ cp) using a capillary of 0.028 inch inner diameter.

Unfortunately at the capillary sizes that are used for sizes $>$ 1,000 μm diameter, the pressure required to create a viable jet (>80 psi) taxes the regulators capacity ability and nears the bursting pressure of the supply lines. This can be overcome in future experiments by using a more sophisticated pressurizing method. However, yet another limitation is imposed upon the system by the effects of a larger cylindrical jet. Even when a viable jet was created with large diameter capillaries it was found that an increasingly larger pressure disturbance amplitude was required. Evidently, the larger jet is naturally more aerodynamically unstable and tends to break up into random size drops sooner than smaller jets. To counteract this, a larger amplitude oscillation is required.

The piezoelectric transducer used (model X-26, Astatic Corporation, Conneaut, Ohio) could not provide the amplitude necessary. A search for other manufacturers and sources revealed that the transducer used was the largest made. If in future experiments, a larger amplitude transducer could be custom manufactured or otherwise obtained, this method would be a viable technique for the production of large drops.

Other methods of forcibly imposing a pressure disturbance were sought. A spring loaded solenoid system was designed which worked effectively in producing a uniform stream. The spring loading, however, created a drop production rate out of synchronization with the source oscillator such that single drops could not be effectively separated from the main stream by the electrostatic deflection technique (see Eaton and Hoffer, 1970). Other techniques such as using a speaker diaphragm similar to Magarvey and Taylor (1956) did not produce a stable, workable drop stream.

The technique finally used for the generation of large drops was simply the dripping of liquid drops from various size capillary tubing. The tubing was either stainless steel or glass. The largest size attainable is limited by the liquid's surface tension. Sizes smaller than 2,000 μm diameter could not be produced by dripping because although very small tubing was used, the wetting action of the liquid on the outside of the tubing always allowed the build up of a substantial amount of liquid.

The drop production rate was always kept less than one every five seconds. Since it took a maximum of three seconds for the drops to traverse the column, any wake effect interaction between drops was negligible (Happel and Brenner, 1965; Eaton and Hoffer, 1970).

C. DROP MASS MEASUREMENT

The drop mass was determined, using either technique of generation, by collecting a drop in a small aluminum foil cup several centimeters below the capillary tubing. The cup, whose weight previous to drop collection is tared out, and drop are weighed on a Cahn 25 Electrobalance which resolves to 10 micrograms for drops of 10 milligrams (2,500 μm diameter). All liquids used had a vapor pressure typically a hundred times lower than water. Since the time between drop collection and settling of the balance was approximately 30 seconds, the mass loss by evaporation was $< 0.01\%$. Any error introduced by evaporation was, therefore, insignificant. In actual measurements, the mass varied for a series of drops by about 1% for large drops, mass > 20 mg, and $<1\%$ for smaller drops. The variation for non-Newtonian liquid drops was slightly greater than Newtonian because of the formation of a thin spider web-like filament that formed when non-Newtonian drops detached from the tubing. The filament broke off from the main drop and itself ruptured to form several very small satellite drops while the majority of the filament settled out.

D. DROP DETECTION AND TIME OF FALL

Equipment for detecting the drop fall is mounted in the lowest section of the column. The basic technique is the detection of forward scattered light as the drop traverses a laser beam. Fiber optics, properly aligned to receive light only from a drop passing through the beam in the center of the column, pick up and transmit the scattered light to a photomultiplier. The output of the photomultiplier is a spike of 0.1-5 volts typically 150 μsec wide with a risetime of about 50 μsec. This signal was then handled by modern operational amplifier integrated circuits of the signal conditioning electronics.

There are five 0.5 mW helium-neon lasers spaced approximately 60 cm apart and aligned vertically and horizontally with a plumb line centered in the column. Their spacing was determined by hanging dimensionally stable aerial film in the column and exposing it to the lasers. In this manner the vertical spacing could be measured to within $\pm$ 0.5 mm. The laser emission which was intially a 1 mm cylindrical beam was expanded by a double convex lens and then focused at the center of the column by a cylindrical lens into an ellipsoid of 5 mm major axis and 1 mm minor axis.

At the opposite side of the column to the lasers, holes were cut and a black box mounted. The black box was necessary to prevent false scattering off the inner walls of the column and still retain a sealed column. It was fabricated from end caps designed for use on four-inch PVC pipe by cutting the cap to fit the circular contour of the column. The inside of the cap was painted black. Due to these precautions and the fact that the fiber optics have such a narrow operature, background noise from the photomultiplier was kept less than 0.02 volts.

The signal conditioning electronics outputs a five volt signal pulse directly to an interrupt input port of a Data General microNova minicomputer. The flow chart of signal processing and computer data processing is depicted in Figure 2. The computer has an internal counter which is initiated upon receipt of a signal, denoting the production of a drop from the drop generation electronics. As signals from the photomultiplier are received, the computer stores the counter value in five successive registers. Thus, the difference of registers 1 and 2 represents the time between lasers 1 and 2, the difference of registers 2 and 3, the time between laser beams 2 and 3, and so forth. Each count difference is converted to time at 21.6 usecs per count. This scheme achieves a resolution

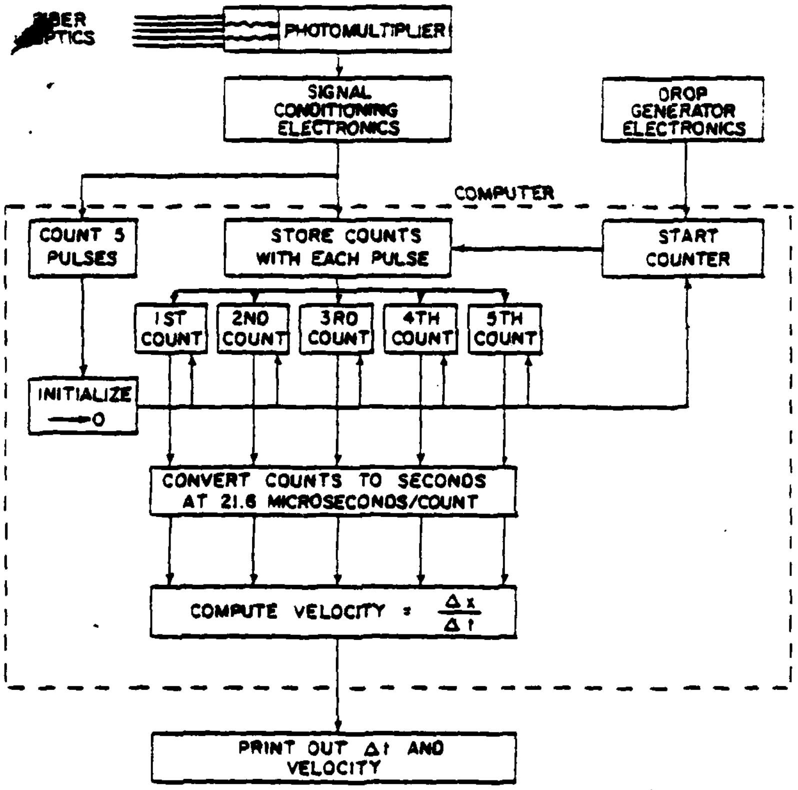

Figure 2: Signal Processing and Computer Data Reduction.

of one part in two thousand or better and is extremely reproducible. In a check, a series of five simulated photomultiplier pulses from a precision pulse generator were fed to the computer. The time interval did not vary by more than one count in the fifth decimal place (one hundred thousandths place). The variation in fall speed from drop to drop is essentially due only to variations in the drop mass.

Two problems were encountered involving the detection of falling drops. Due to the sensitivity of the detaching drop to the roughness of the tubing tip and the severe distortion and oscillation of large drops, very few of the drops fall along the vertical. However, as discussed previously, this does not affect the data since the alignment of the lasers and fiber optics insured that only drops which fall vertically in the center of the column were measured.

Secondly, during measurements with the forced breakup of a cylindrical jet technique the drop stream was difficult to align with the center of the column. It appeared that the drop stream was hitting the walls before reaching the level of the lasers. At first it was thought turbulence inside the column was reponsible and so necessary steps were taken to insure hydrostatic stability within the column (see A Fall Column). This did not entirely solve the problem so an approximate estimation was made of the trajectory of the ejected drops. The calculation is shown in appendix A and shows that the ejected drop must be within 1° of vertical if it is to fall the 11 meters without hitting the walls of the column.

V. DATA REDUCTION

Measurements of the fall velocity consist of a set of up to four time intervals resulting from a drop traversing through two or more lasers; i.e., traversing all five lasers gives four time intervals. Each time interval corresponds to a laser spacing inteval. Data reduction then consists of calculating the terminal velocity from the set of measured velocities. Because of the differing behavior of large and small drops, the terminal velocity is computed differently for each size range.

In the range $100 < Re < 200$ measured, the drops reach terminal velocity in only a few meters. The drops are essentially spherical and do not oscillate, thus once the drop stream is aligned with the laser beams, every drop successfully traverses all five lasers. There is no acceleration so that the terminal velocity is taken as the average of the four velocity intervals measured.

The larger drops ($Re > 800$) are known to be highly deformed and oscillate about their equilibrium shape; consequently, only a few drops are able to successfully pass through all five laser beams. When a run was made with a given drop size of say a hundred drops, perhaps one or two would successfully traverse all five lasers. Those measurements accepted were those in which at least three laser beams were hit. In 98% of all measurements it turned out that the first laser was always hit and at least four beams hit. Although the lasers were nearly equally spaced, the extreme accuracy of the computer timing loop enabled one to determine which lasers were hit and which missed. Thus, if only three or four time intervals were measured, each interval could be properly identified corresponding to the appropriate space interval. The larger drops showed a slight acceleration in the computed velocity intervals. To compute the terminal velocity of a given drop size, all measurements of the

same interval were averaged, the four resulting velocities were then fitted with an equation of the form

$$V = A \exp(-B/t).$$

It is evident that the terminal velocity is the coefficient A. In all cases the difference in the velocity of the last interval and the velocity of the first interval was $\geq 0.5\%$. The velocity of the last interval was always $\leq 99.5\%$ of the computed terminal velocity.

The scatter of the actual velocities as indicated by one standard deviation was typically 0.5% of the mean for a given velocity interval. Because of the measurement system used and its highly reproducible results, any calculations based on the measurements can be expected to be accurate and reliable. The Reynolds number and drag coefficient were computed from equations (4) and (3) respectively.

VI RESULTS AND DISCUSSIONS

A first series of measurements were taken using three Newtonian liquids of differing surface tensions and viscosities: Propylene Glycol Isobutyl Ether (PiBT), Ethylene Glycol (EG), and Dipropylene Glycol Methyl Ether (DPM). Their relevant physical properties are given in Table 1. The results of measurements, plotted in Figure 3, immediately indicate the importance of drop liquid viscosity affecting the drag via the internal circulation. The liquids PiBT and DPM, are essentially of equal surface tension while only their viscosity differs yet PiBT's C_D is almost 20% greater (Re=1000). This is indicative of decreased internal circulation which acts via frictional drag and pressure drag. Reduced internal circulation increases shear at the drop surface and boundary layer separation occurs sooner resulting in a greater pressure drop in the wake. This general effect is also evidenced by the results of Buzzard and Nedderman (1967), however, the results reported here do not agree in two respects; first in the trend of the drag curve above Re=1000, secondly in the absolute values. They show a flattening of the C_D curve as Re→2000 and their silicone fluids of comparable surface tension and viscosity exhibit drag coefficients $\sim$5 - 10% lower. Our results parallel the trend of the well-established established C_D curve of water and our self-check measurements with water give terminal velocities with 1% agreement with Davies (1939, unpublished) reported in Best (1950) for an altitude of 5,000 feet ($\rho_a = .989 \frac{gms}{ml}$).

Measurements were taken at Re=100-200 for PiBT and EG which show that the effect of internal circulation in reducing the drag is comparatively more dramatic than at higher Re. The PiBT and EG curves cross at about Re=500 although PiBT's surface tension should place it above EG throughout the entire Re range. At this low Re range the drops will be more closely spherical

TABLE I

LIQUID PROPERTIES

Liquid	ρ_{ℓ}(gms/ml)	μ(centipoises)	σ(dynes/cm)
Ethylene Glycol (EG)	1.106	19.90	48.40
Propylene Glycol Isobutyl Ether (PiBT)	0.971	10.86	26.90
Dipropylene Glycol Methyl Ether (DPM)	0.951	3.41	28.80
Newtonian thickened DPM's			
N1	0.953	3.94	∿29.00
N2	0.958	5.04	
N3	0.975	23.21	
N4	1.020	453.00	
N5	0.964	8.60	
Non-Newtonian thickened DPM's			
NN1	0.956	47.90	29.18
NN2	0.958	104.40	
NN3	0.958	268.00	29.36
NN4	0.953	6.86	
NN5	0.953	4.86	

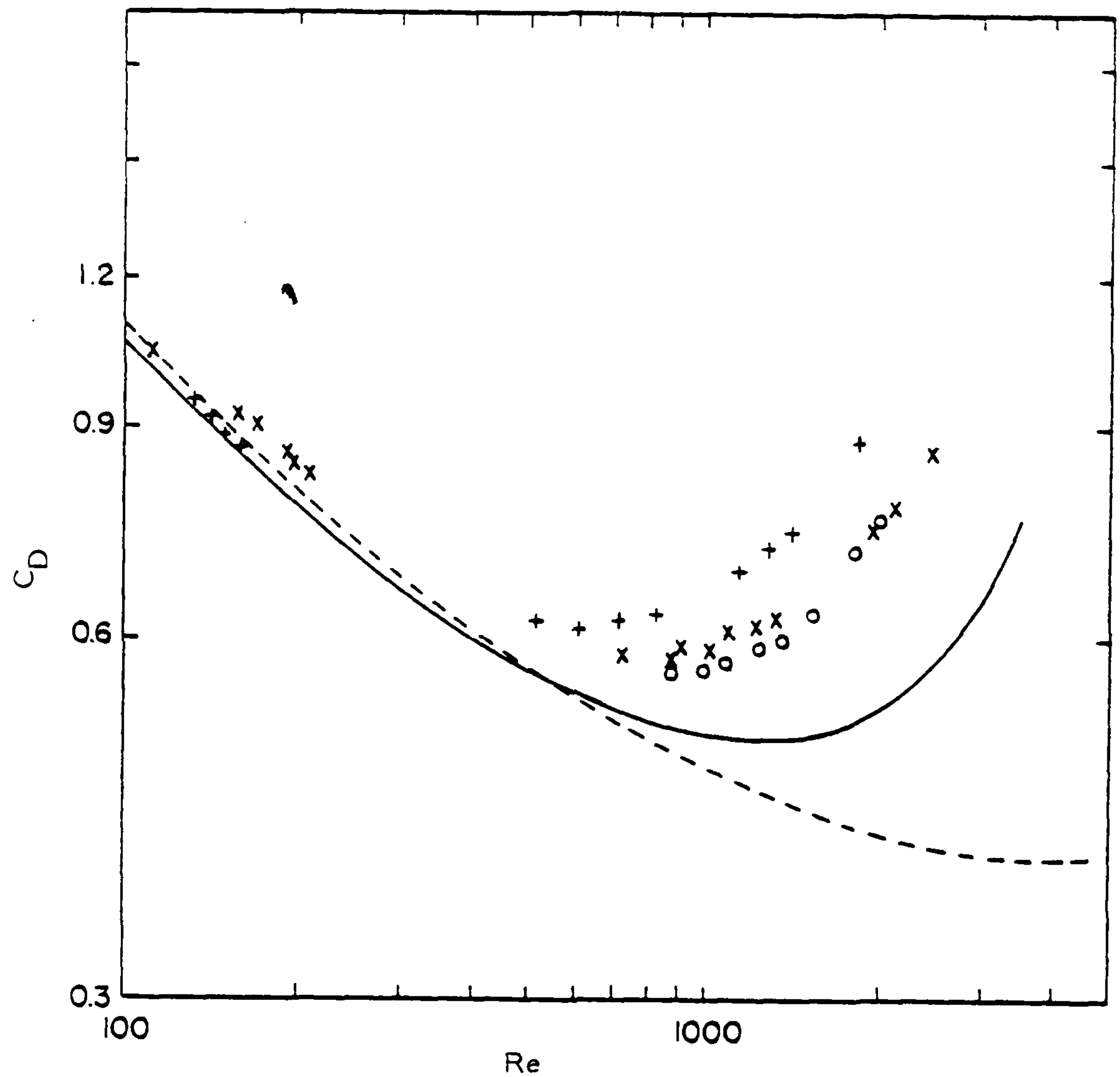

Figure 3: Reynolds number (Re) versus drag coefficient (C_D). Solid line is for water (Gunn and Kinzer, 1949); dashed line for sphere (Davies, 1945): o-DPM, x-EG, +-PiBT (see Table 1).

and the surface area available for traction by the air is greater. Thus the surface shear is more effective in transporting momentum to the internal fluid at lower Re due to the more spherical shape. Theoretical calculations by LeClair et al. (1972) for a rigid water sphere show that the drag at Re=100 is evenly divided between friction and pressure drag. LeClair et al, also calculated the velocity of the drop liquid at the surface and show that the internal circulation levels off for Re>800. A limiting of internal circulation implies that drop distortion should eventually control the drag in the limit of higher Re. Our results corroborate this limiting of internal circulation. The curve of DPM becomes steeper than EG and crosses at Re$\sim$1800 so that the effect of drop distortion on drag predominates at higher Re. Greater distortion which acts to increase the pressure drag shifts the minimum of the drag curve to lower Re. The minimum can then be interpreted to represent the point at which drop distortion limits the surface area available for traction thereby limiting the internal circulation.

In order to quantitatively assess the effect of viscosity on drag a series of measurements were taken in which the viscosity was changed while the surface tension was constant. For this task, DPM was thickened with two thickeners: 1. Elvacite (CH_2: $C(CH_3)COOCH_3$) an acrylic resin monomer; 2. Akryloid K-125, a methyl methacrylate resin polymer. DPM thickened with Elvacite produces Newtonian fluid whereas Akryloid K-125 results in a non-Newtonian fluid exhibiting visco-elastic properties. Thus, any differences in internal circulation for Newtonian and non-Newtonian liquids will be tested.

The results for Newtonian thickened DPM are shown in Figure 4 and non-Newtonian thickened DPM in Figure 5. Both show the decrease of drag with decrease of viscosity and show the paralleling of curves in this Re range.

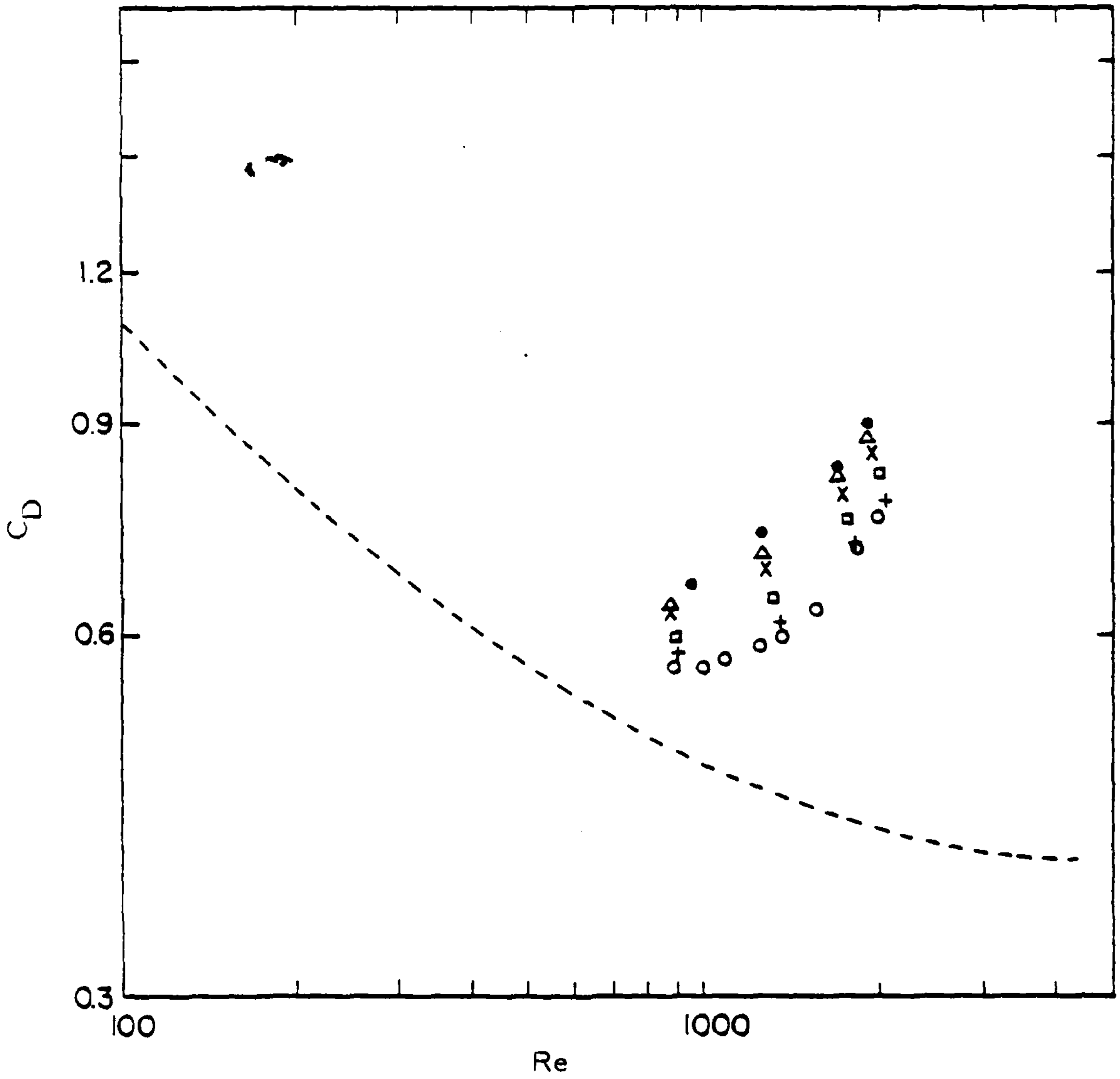

Figure 4: Reynolds number versus drag coefficient for Newtonian thickened DPM: o-3.41 cp, +-3.94 cp, □-5.04 cp, x-8.60 cp, ▲-23.21 cp, ● -453 cp.

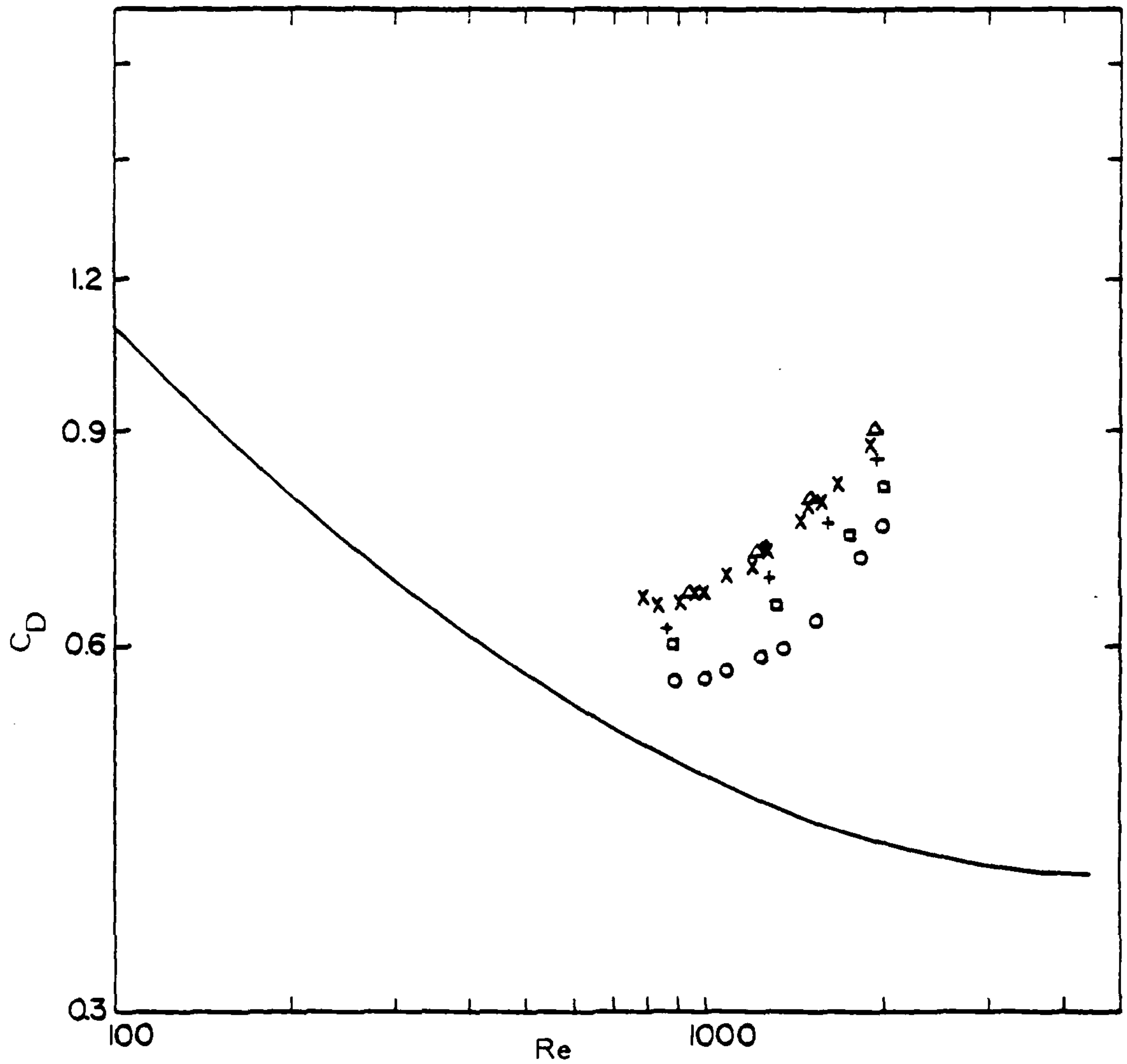

Figure 5: Reynolds number versus drag coefficient for non-Newtonian thicked DPM: o-3.41 cp, ◘-4.86 cp, +-6.86 cp, x-47.90 cp, ▲-104.4 cp, ●-268 cp.

The plot of μ versus C_D, Figure 6, shows that there is no difference between Newtonian and non-Newtonian fluids. A quantitative assessment of μ versus C_D can be successfully approached by considering the mathematical functional form necessary to fit the experimental data and exhibit appropriate limiting properties. The Stokes solution, equation (8), strongly suggests that internal circulation is determined by the ratio μ_a/μ. The analysis of the proper mathematical function of μ_a/μ will now be considered.

Let us consider the functional relation

$$C_D = F(Re, \frac{\mu_a}{\mu})$$

and assume

$$C_D = F(Re)\ F(\frac{\mu_a}{\mu})$$

In the above relation we are in effect assuming that the contributions of drop shape and internal circulation can be separated. The drop shape acts through F(Re) since it may also contain an appropriate shape parameter. Now if we form the ratio of two (2) C_D's (two liquids of equal surface tension but differing viscosity) we get

$$\frac{C_{D1}}{C_{D2}} = \frac{F(\frac{\mu_a}{\mu_1})}{F(\frac{\mu_a}{\mu_2})}$$

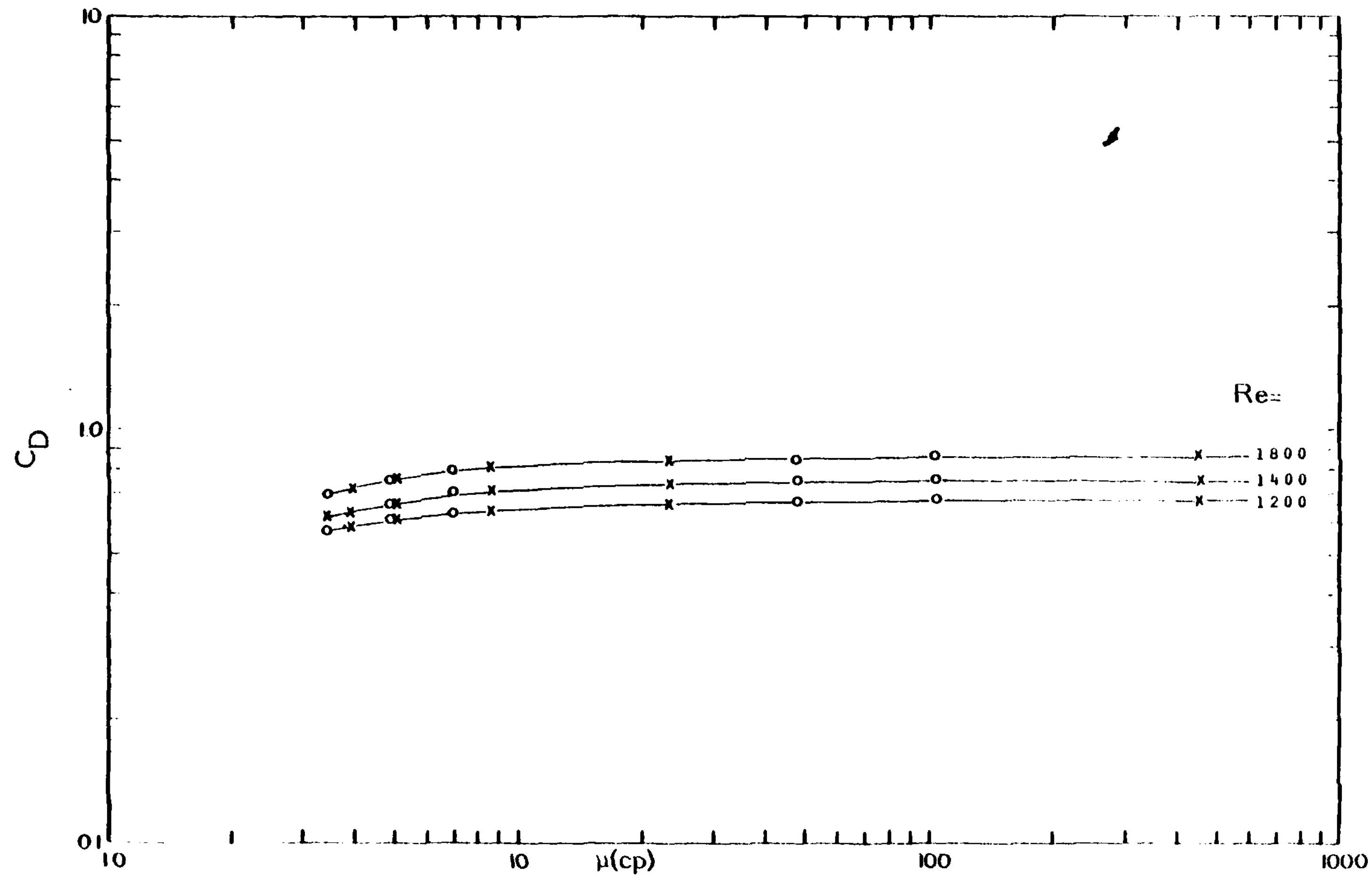

Figure 6: Viscosity (centipoises) versus drag coefficient for Newtonian (x) and non-Newtonian (o) thickened DPM.

a relation independent of drop shape. If we assume

$$F\left(\frac{\mu_a}{\mu}\right) = \left(\frac{\mu_a}{\mu}\right)^x$$

This will result in

$$\frac{C_{D1}}{C_{D2}} = \left(\frac{\mu_2}{\mu_1}\right)^x \quad .$$

However, the experimental results indicate that this functional form is inappropriate because we have

$$\frac{C_{D1}}{C_{D2}} \neq \frac{C_{D3}}{C_{D4}}$$

even if

$$\frac{\mu_2}{\mu_1} = \frac{\mu_4}{\mu_3}$$

For example:

$$\frac{\mu_2}{\mu_1} = \frac{\mu_4}{\mu_3} = 2.18$$

but

$$\frac{C_{D1}}{C_{D2}} = 0.89 \neq \frac{C_{D4}}{C_{D3}} = 0.98$$

This result says that

$$\frac{C_{D1}}{C_{D2}} = \frac{F(\mu_1 \pm \mu_a)}{F(\mu_2 \pm \mu_a)}$$

i.e., the function must be a function of a sum or difference. The difference from physical reasoning is $\mu \pm \mu air$. The function

$$F(\frac{\mu_a}{\mu}) = 1\text{-}B \ (\frac{\mu_a}{\mu})^x \tag{9}$$

has this property since it can be rewritten as

$$F(\frac{\mu_a}{\mu}) = \frac{1}{\mu^x} (\mu^x - B\mu^x_a) \ .$$

It also has the desirable limiting property

$$F(\frac{\mu_a}{\mu}) \rightarrow 1, \frac{\mu_a}{\mu} \rightarrow 0.$$

We can write then

$$C_D = F(Re)[1\text{-}B(\frac{\mu_a}{\mu})^x] \tag{10}$$

but F(Re) is just the drag coefficient for a non-circulating (infinite viscosity) deformable drop, say C_D ($\mu = \infty$), which can be obtained from Figure 6. So B and x can be found from

$$1 - \frac{C_D}{C_D(Re,\mu=\infty)} = B\left(\frac{\mu_a}{\mu_\ell}\right)^x$$

by least squares fit of the equation to data which is plotted in Figure 7 for Re=1000 only. Equation (10) is reminescent of Hadamard's (1911) solution for Stokes flow about a fluid sphere

$$C_D = C_{D_o}(1-1/3\frac{\mu_a}{\mu})$$

where C_{D_o} is the Stokes drag of a solid sphere. The computed values are x = 0.974 and B = 1/25.9 at Re=1000 with a correlation of 0.99. The value of the exponent is strikingly close to 1.0 and it is not unreasonable to assume it should be x = 1.0. The form of Equation (10) may very well be general; however, it is clear that the viscosity function cannot be entirely independent of Re all the way down to the Stokes region nor as $Re \to \infty$. The similarity of the Stokes flow solution to that for higher Re suggests the slightly more generalized viscosity function

$$F(Re,\frac{\mu_a}{\mu}) = 1 - B\frac{\mu_a}{\mu} f(Re)$$

where f(Re) would be a weak function of Re. For example, if

$$C_D = C_D(Re,\mu=\infty)\ (1-B\frac{\mu_a}{\mu}Re) \tag{11}$$

then B = 1/30 gives the Stokes flow solution at Re=10 and excellent agreement with experimental data at Re=1000. In order to be definitive, however, requires

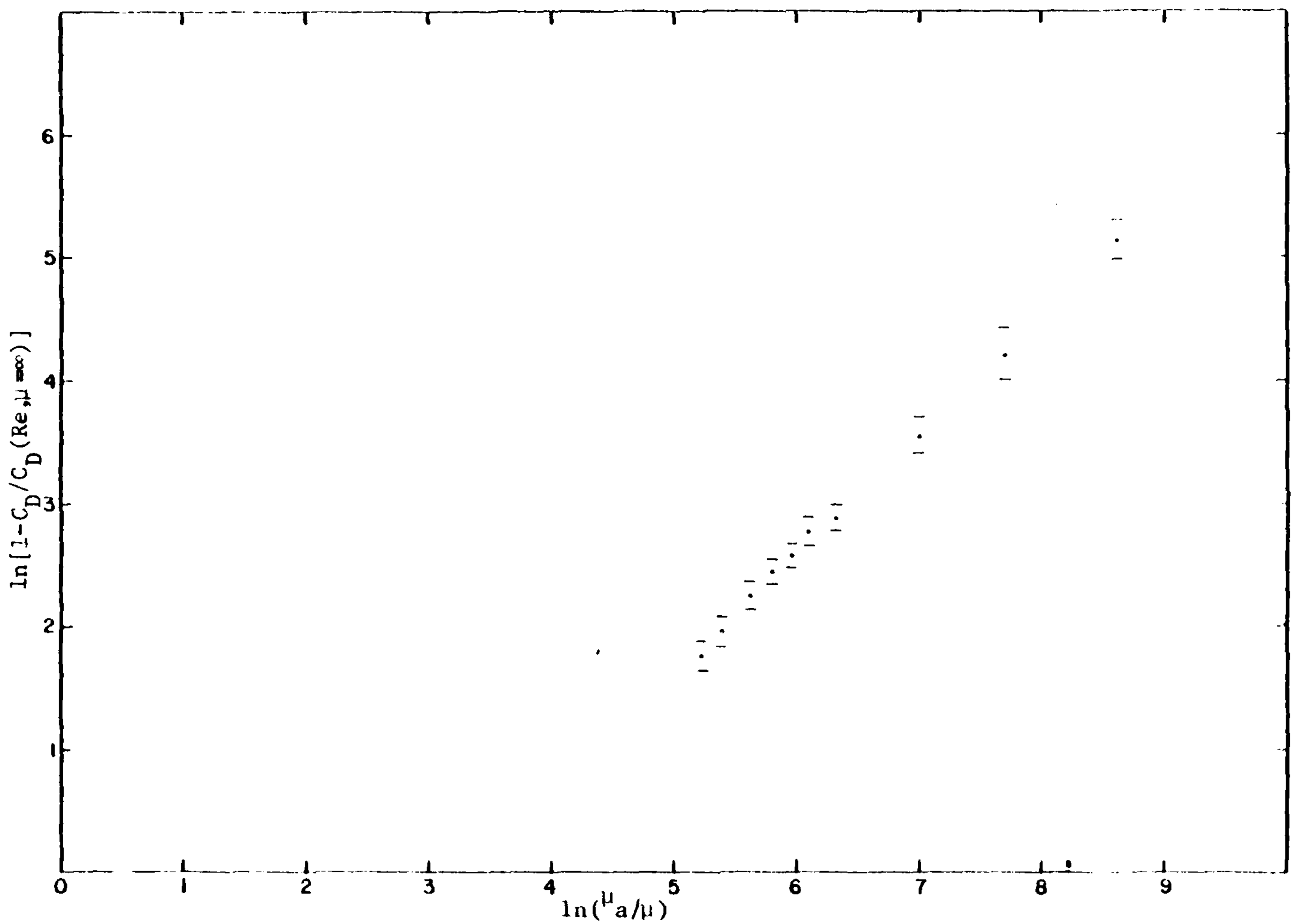

Figure 7: The relation of the viscosity ratio (μ_a/μ) to the viscosity function expressed by equation (9).

measurements to extend the curves for DPM (Figures 4 and 5) down to the Stokes region.

If the viscosity function as expressed by Equation (11) is tested against experimental data at higher Re (e.g., Re=1800), the linearity of $^{\mu}a/\mu$ is preserved but the coefficient, B, must be adjusted smaller in order for Equation (11) to be accurate. Thus, the functional dependence on Re is not yet completely expressed by the form of Equation (11). However, by defining an internal circulation non-dimensional number as

$$N_{IC} = \frac{\mu_o}{\mu_i} Re$$

where μ_o and μ_i are the viscosities of the external and internal fluid mediums, Equation (11) is entirely satisfactory if the following condition is met

$$(BN_{IC})^2 << 1. \tag{12}$$

The condition Equation (12) and the functional form of Equation (11) are characteristic of a power series expansion in which all terms of second and higher order are neglected. It is suggested that Equation (11) is the truncated series expansion of a general function of N_{IC} and in general the drag coefficient of a finite viscosity liquid drop is expressed by

$$C_D = F(Re, N_{IC}).$$

VII SUMMARY

The experimental results show the effects of physical properties upon the drag. Liquids of lower surface tension increase the drag corresponding to increased distortion of the drop shape. The increased distortion shifts the minimum of the drag curve upward and toward lower Reynolds number.

Liquids of lower viscosity decrease the drag. The viscosity governs the degree of internal circulation that develops within the drop. Increased internal circulation decreases shear at the drop surface and retards boundary layer separation. Thus, the fraction and pressure drag are both reduced. Quantitatively the lowering of the drag can be expressed by equation (11) if the condition expressed by equation (12) is met.

In addition, for Newtonian and non-Newtonian liquids the effect of viscosity is identical.

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IX. ACKNOWLEDGEMENTS

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APPENDIX A: DROP TRAJECTORY ANALYSIS

An analysis of the trajectory of a drop ejected from a capillary tube inclined at an angle β from the vertical is presented here. This analysis was necessary in order to determine if non-vertical alignment of the capillary caused drops to hit the inner walls of the column before reaching the measurement section. Because of difficulties in detecting the drops it was thought that drops might be horizontally displaced enough from the center of the column to hit the walls. An approximate estimation can be approached by considering the equations of motion for the falling drop.

The ejection velocity of a drop from the capillary tube can be assumed to be the terminal velocity (V_T). This assumption is born out by the measurements which show that the velocity calculated from the elapsed time between drop creation and detection by the first laser is 75% of terminal. If the angle from the vertical of the capillary tube is β, then the horizontal component of velocity is

$$V_x = V_T \tan\theta \tag{A1}$$

Taking V_T = 3.5 m/s (r = 0.5 mm) and $\beta = 5^o$, then V_x = 30 cm/sec. The Reynolds number calculated from this velocity and size is well within the Stokes region for the expression of drag on the drop. Thus as the horizontal equation of motion we have

$$ma_x = -6\pi r \mu_a V_x. \tag{A2}$$

Integrating we get

$$V = V_{xo} \exp(-\frac{9\mu_a t}{2 r^2}) . \tag{A3}$$

Where V_{xo} is given by equation (A1). Integrating again to get the horizontal displacement,

$$X = \frac{2r^2}{9\mu_a} \rho_\ell V_{xo} [1-\exp(\frac{9\mu_a t}{2r^2\rho_\ell})] \quad . \tag{A4}$$

From this expression one can calculate the horizontal displacement as a function of time. However, time can be eliminated and a more convenient expression arrived at by considering vertical motion. Since the angle β is small, the vertical velocity is essentially the ejection velocity which is assumed to be terminal. Thus the vertical displacement is

$$y = V_T t. \tag{A5}$$

Using equation (A5) to eliminate t in (A4) we have

$$X = \frac{2 r^2}{9\mu_a} \quad V_{xo} [1-\exp(\frac{9\mu_a}{2 r^2\rho_\ell} \frac{y}{V_T})]. \tag{A6}$$

Now x can be calculated given typical values of r and V_T. V_{xo} is calculated from (A1) and y is specified. The following table shows the results of some sample calculations.

TABLE A-1

HORIZONTAL DISPLACEMENT

β	y = 10m V_T = 3.5 m/s	y = 11m V_T = 3.5 m/s
	X(mm)	X(mm)
1.0°	113	120
0.5°	57	60
0.15°	26	30

Since the inner radius of the column is 76 mm (3 inches) any horizontal displacement over 76 mm implies the drops hit the wall. It can be seen that it requires $\beta < 1^{\circ}$ if the drops are to be detected by the lasers. The micrometer stage is attached to the roof with turnbuckles so that it could be leveled appropriately.

APPENDIX B: DATA FILES AND IDENTIFICATION LISTING

RAWDAT - time intervals;
VTDT - velocity intervals;
RECD - computed Reynolds number and drag coefficient.

	File		Identification
RAWDAT1	VTDT1	RECD1	Pure ethylene glycol
RAWDAT2	VTDT2	RECD2	Dowanol PiBT
RAWDAT3	VTDT3	RECD3	Thickened ethylene glycol
RAWDAT4	VTDT4	RECD4	Pure Dowanol DPM
RAWDAT5	VTDT5	RECD5	Non-Newtonian thickened DPM1
RAWDAT6	VTDT6	RECD6	Non-Newtonian thickened DPM2
RAWDAT7	VTDT7	RECD7	Non-Newtonian thickened DPM3
RAWDAT8	VTCT8	RECD8	Non-Newtonian thickened DPM4
RAWDAT9	VTDT9	RECD9	Non-Newtonian thickened DPM5
RAWDT10	VTDT10	RECD10	Newtonian thickened DPM1
RAWDT11	VTDT11	RECD11	Newtonian thickened DPM2
RAWDT12	VTDT12	RECD12	Newtonian thickened DPM3
RAWDT13	VTDT13	RECD13	Newtonian thickened DPM4
RAWDT14	VTDT14	RECD14	Newtonian thickened DPM5

RAWDAT1

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 0.076715 0.076780 0.076481 0.076456
 0.076737 0.076737 0.076442 0.076417
00.0
 5
014.9870
 0.075008 0.075075 0.074793 0.074512
00.0
 6
020.2000
 0.073453 0.073432 0.072935 0.072762
 0.073388 0.073475 0.0730[illegible]3 0.072827
00.0
 7
031.7400
 0.072006 0.072070 0.071768 0.071617
00.0
 8
039.9700
 0.071206 0.071358 0.071033 0.070990
00.000001
```

RAWDAT5

```
0.956
 1
006.000
 0.090329 0.090587 0.090283 0.090119
00.0
 2
007.182
 0.087539 0.087885 0.087691 0.087710
00.0
 3
008.214
 0.085983 0.086524 0.086342 0.086386
 0.086156 0.086588 0.086429 0.086449
00.0
 4
008.704
 0.086287 0.086422 0.085897 0.085832
00.0
 5
010.787
 0.084460 0.084718 0.084298 0.084061
 0.084428 0.084666 0.084277 0.084267
 0.084699 0.084718 0.084147 0.084061
00.0
 6
013.547
 0.081857 0.082008 0.081771 0.081727
 0.081814 0.082138 0.081792 0.081619
 0.082138 0.082095 0.081879 0.081727
00.0
 7
015.500
 0.081231 0.081339 0.081123 0.081036
 0.081231 0.081231 0.081014 0.080928
 0.081187 0.081555 0.080885 0.081014
00.0
 8
021.330
 0.079092 0.079308 0.079070 0.078897
00.0
 9
 23.140
 0.079049 0.079243 0.078941 0.078789
 0.079394 0.079675 0.079416 0.079265
00.0
10
025.85
 0.077990 0.078185 0.077947 0.077796
00.0
11
030.550
 0.076954 0.077363 0.077104 0.076953
00.0
12
042.480
 0.075952 0.076139 0.075851 0.075722
00.000001
```

```
RAWDATS



0.958
 1
  7.940
 0.087150 0.087452 0.087020 0.087011
00.0
 2
 14.39
 0.081871 0.082060 0.081684 0.081749
 0.082161 0.082397 0.082095 0.082073
00.0
 3
 24.09
 0.079135 0.079329 0.079092 0.078919
00.0
 4
 45.38
 0.076110 0.076326 0.076002 0.075938
00.000001
```

```
RAWDAT7



0.958
 1
015.4900
 0.081511 0.081619 0.081468 0.081295
 0.081792 0.081792 0.081468 0.081360
00.000001
```

```
RAWDAT3



0.953
 1
  6.160
 0.087971 0.088209 0.087971 0.087979
00.0
 2
 15.07
 0.079783 0.079913 0.079593 0.079563
00.0
 3
 26.48
 0.076370 0.076629 0.076283 0.076175
00.0
 4
 43.15
 0.074901 0.075138 0.074987 0.074876
 0.074793 0.074814 0.074663 0.074555
00.000001
```

RAWDAT2

```
0.953
 1
  5.400
 0.086199 0.086459 0.086156 0.086137
 0.086394 0.086632 0.086329 0.086312
 0.086216 0.086466 0.086113 0.086048
00.0
 2
 15.136
 0.077801 0.077904 0.077515 0.077428
00.0
 3
 30.73
 0.073885 0.073972 0.073626 0.073561
00.0
 4
 43.58
 0.072891 0.072935 0.072740 0.072677
 0.072805 0.072913 0.072589 0.072524
00.000001
```

```
RAWDT10


0.953
 1
  6.374
 0.084903 0.085095 0.084798 0.084612
00.0
 2
 15.006
 0.075873 0.075938 0.075592 0.075524
00.0
 3
 31.58
 0.072373 0.072330 0.072092 0.071876
 0.072351 0.072222 0.071984 0.071833
00.0
 4
 43.97
 0.071403 0.071529 0.071163 0.071098
 0.071461 0.071514 0.071120 0.070969
 0.071490 0.071528 0.071142 0.071012
00.000001
```

```
RAWDT11



0.958
 1
  6.508
 0.085892 0.086052 0.085659 0.085551
00.0
 2
 14.912
 0.077557 0.077731 0.077428 0.077255
 0.077536 0.077666 0.077417 0.077251
00.0
 3
 31.58
 0.074015 0.074058 0.073669 0.073518
 0.074036 0.074058 0.073756 0.073561
 0.073842 0.074015 0.073604 0.073583
00.0
 4
 43.90
 0.072978 0.073129 0.072783 0.072675
00.000001
```

RAWDT12

```
0.975
 1
  6.648
 0.087582 0.087569 0.087338 0.087236
00.0
 2
 13.053
 0.080150 0.080345 0.080107 0.079999
00.0
 3
 31.64
 0.076322 0.076526 0.076154 0.076002
 0.076456 0.076629 0.076325 0.076204
00.0
 4
 43.13
 0.075203 0.075397 0.075203 0.074987
 0.075170 0.075376 0.075009 0.074857
 0.075397 0.075549 0.075289 0.075222
00.000001
```

```
RAWDT13



1.029
 1
  3.133
 0.084752 0.084925 0.084666 0.084635
 0.084838 0.085023 0.084795 0.084779
00.0
 2
 15.599
 0.079697 0.079848 0.079771 0.079635
00.0
 3
 31.55
 0.075700 0.075765 0.075592 0.075614
 0.075959 0.076002 0.075700 0.075592
00.0
 4
 44.21
 0.075218 0.075094 0.074685 0.074598
 0.075407 0.075329 0.074901 0.074771
00.000001
```

```
RAWDT14


0.964
 1
  5.400
 0.088150 0.088222 [illegible] [illegible]
 0.087452 0.087777 0.087474 [illegible]
00.0
 2
 14.364
 0.079589 0.079761 0.079481 0.079265
00.0
 3
 31.49
 0.075484 0.075635 0.075333 0.075225
 0.075484 0.075572 0.075225 0.075095
 0.075417 0.075549 0.075117 0.075073
 0.075549 0.075570 0.075246 0.075138
00.0
 4
 43.090
 0.074555 0.074555 0.074305 0.074292
 0.074645 0.074804 0.074404 0.074231
 0.074729 0.074897 0.074577 0.074533
 0.074663 0.074836 0.074452 0.074274
 0.074664 0.074776 0.074360 0.074231
00.000001
```

[illegible]

1.106

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3.060161	3.068001	3.073633	3.071457
3.065244	3.068674	3.075001	3.071128
3.063893	3.067657	3.073633	3.072132
3.061854	3.066312	3.072956	3.072477
3.062873	3.066984	3.073302	3.071802
3.062199	3.068001	3.074325	3.073498
3.063893	3.068330	3.072956	3.074174

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809.3

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3.590501	3.583749	3.597382	3.592877
3.589100	3.582362	3.598308	3.597994
3.587249	3.585586	3.597834	3.595670
3.580290	3.579590	3.593185	3.595219
3.583057	3.577759	3.593185	3.587796
3.589574	3.587396	3.600638	3.591032
3.572988	3.572701	3.587627	3.586875
3.577034	3.580059	3.593658	3.590560
3.580290	3.583749	3.596456	3.591503
3.577505	3.582362	3.595508	3.590560
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3.577976	3.583279	3.591810	3.583626
3.578426	3.580975	3.590415	3.588717
3.577505	3.576376	3.589920	3.583626
3.577505	3.576376	3.589920	3.583626
3.578426	3.579143	3.590415	3.585734
3.580290	3.579590	3.592734	3.588717
3.574725	3.573168	3.587156	3.583626
3.577034	3.575909	3.589471	3.590560
3.578426	3.576376	3.586706	3.585015
3.578897	3.581444	3.593185	[illegible]
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3.582134	3.583108	3.592734	[illegible]
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3
[illegible]44.6

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3.683685	3.688668	3.710231	3.695452
3.698929	3.697488	3.708084	3.714811
3.689573	3.693560	3.706734	[illegible]
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3.687593	3.688173	3.702731	[illegible]
3.684661	3.684759	3.694901	[illegible]
3.685138	3.690637	3.703231	[illegible]
3.682687	3.686724	3.701777	[illegible]
3.691052	3.688668	3.698837	[illegible]
3.686615	3.685255	[illegible]	[illegible]
3.693994	3.689641	3.702731	[illegible]
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3.694998	3.695535	3.705248	3.696451
3.690073	3.694059	3.706231	3.700865
3.694496	3.692087	3.702279	3.695452
3.685138	3.692087	3.701278	3.692524
3.686138	3.689641	3.700318	3.690077
3.692032	3.702404	3.707718	3.699385
3.684661	3.685730	3.694901	3.689578
3.696460	3.695535	3.703261	3.701367
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3.698929	3.700924	3.712163	3.706775

4
398.9

3.916686	3.917010	3.931023	3.917040
3.913354	3.909297	3.926039	3.920335
3.918893	3.922528	3.933237	3.921997
3.916686	3.912602	3.929352	3.923661
3.924449	3.918107	3.933804	3.924762
3.924449	3.915353	3.929352	3.924762
3.919998	3.922528	3.932696	3.928095
3.926665	3.915914	3.930457	3.913674
3.917789	3.917546	3.927682	3.926992
3.917789	3.913162	3.929352	3.925326
3.911690	3.909856	3.927142	3.921997
3.917225	3.910415	3.927142	3.924224
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3.906170	3.903816	3.923269	[illegible]
3.925556	[illegible]	3.927682	3.920997
3.912253	3.909856	3.927142	[illegible]
3.912790	3.927113	[illegible]	[illegible]
3.908922	3.904931	3.921041	[illegible]
3.906732	[illegible]	3.918279	3.920335
3.915557	3.914257	[illegible]	[illegible]
[illegible]	3.914792	3.927142	[illegible]
3.913121	3.938219	3.938612	[illegible]

5
[illegible]

[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]
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4.072851	[illegible]	4.084647	[illegible]
4.080071	4.078610	[illegible]	[illegible]
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4.083670	4.084224	4.094252	[illegible]
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4.080661	4.086610	[illegible]	[illegible]
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4.084870	4.084224	4.094252	[illegible]
4.086098	4.086100	[illegible]	[illegible]
4.087886	4.088416	[illegible]	[illegible]
4.089116	4.089611	[illegible]	[illegible]

7
1917.7

6.876811	6.893351	6.932016	6.931635
6.873412	6.900151	6.930257	6.926524

8
2185.6

7.332230	7.367622	7.402642	7.391903
7.389037	7.402895	7.444293	7.451357
7.371276	7.400891	7.440236	7.437347
7.361475	7.393068	7.438301	7.443332
7.396898	7.406815	7.454270	7.453297
7.349803	7.383267	7.422400	7.427424
7.396898	7.406815	7.450202	7.467274
7.379189	7.402895	7.438301	7.439371
7.367371	7.393068	7.424418	7.419542
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9
2251.6

7.385113	[illegible]	7.434342	[illegible]
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7.375276	7.404804	[illegible]	[illegible]
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7.375270	7.402895	[illegible]	[illegible]
[illegible]	[illegible]	7.440236	[illegible]

10
[illegible]

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

7.616803	7.667248	7.708232	[illegible]
7.639867	7.672174	7.708438	[illegible]
7.627867	7.673404	7.722[illegible]	7.72[illegible]
7.642015	7.672174	7.70[illegible]	7.7[illegible]48
7.637817	7.66[illegible]	7.725589	[illegible]
7.644766	7.668999	[illegible]	[illegible]
7.663168	7.672174	[illegible]	7.741[illegible]
7.646215	7.670042	[illegible]	[illegible]
7.642015	7.673462	7.71[illegible]54	[illegible]
7.621422	7.71[illegible]	7.72[illegible]	[illegible]
7.644[illegible]	7.680[illegible]	[illegible]	[illegible]
7.642015	7.6827[illegible]	[illegible]	[illegible]
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7.653948	7.691[illegible]	7.733413	[illegible]
7.654631	7.670042	[illegible]	[illegible]
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7.673789	7.682777	7.727676	7.739390
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7.658790	7.693390	7.734144	7.735009
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11
2579.1

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7.755499	7.801152	7.832164	7.848499
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12
2790.9

7.981367	8.049[illegible]	8.106233	8.120075
8.0[illegible]054	8.058574	8.1[illegible]8531	8.11[illegible]
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8.0[illegible]054	8.[illegible]	8.115[illegible]	8.120075
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7.[illegible]	8.[illegible]	8.[illegible]	8.[illegible]

13
[illegible]

8.189[illegible]	8.[illegible]	8.[illegible]	[illegible]
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8.1[illegible]	[illegible]	8.[illegible]	[illegible]
8.[illegible]	8.[illegible]	[illegible]	[illegible]
[illegible]	8.[illegible]	[illegible]	[illegible]
8.1[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

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8.184332	8.225191	8.265[illegible]	[illegible]
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8.177512	8.220[illegible]	8.22[illegible]	[illegible]
8.172252	8.211595	[illegible]	[illegible]
8.181818	8.220753	8.22[illegible]	[illegible]
8.177[illegible]	8.21[illegible]	[illegible]	[illegible]
8.191619	8.229839	8.274[illegible]	[illegible]

14
4024.[illegible]

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8.745466	8.821976	8.867005	8.917183
8.748153	8.816416	8.852015	8.894494
8.737160	8.816416	8.837948	8.880306
8.756480	8.844418	8.837948	8.9[illegible]155

15
4337.0

8.857388	8.941047	8.957619	8.997920
8.877244	8.958225	8.983609	9.015459
8.868686	8.952492	8.966176	9.006681
8.874477	8.955424	8.977835	9.024255
8.885818	8.966905	8.995313	9.035918
8.871580	8.955424	8.983609	9.027100
8.877244	8.963965	8.995313	9.041761
8.868686	8.966905	8.983609	9.035918
8.868686	8.955424	8.974884	9.009650
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8.871580	8.958225	8.977835	9.018434
8.880144	8.981365	8.977835	9.024255
8.885818	8.961161	8.974884	9.021276
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8.882914	8.961161	8.980788	9.021276
8.877244	8.975602	8.992350	9.033067
8.880144	8.966905	8.977835	9.015459
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16
4926.[illegible]

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766.2

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3.217385	3.224337	3.232278	3.222616
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3.195669	3.199128	3.206192	3.197798
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3
[illegible]

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3.415077	3.416216	3.424161	3.415204
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3.520615	3.524758	3.532934	3.525090
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8.046342	8.089026	8.122786	8.144812
8.041689	8.084243	8.115652	8.135224
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3794.7

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4213.3

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2590.7

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2732.8

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4489.2

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.958

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VTDTB

.953

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3757.9

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VTOT12

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3088.1

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3966.2

7.921944	7.952667	7.973664	7.992689
7.921944	7.957191	7.985111	8.006525
7.928771	7.961720	7.996592	8.008871
7.915128	7.959508	7.982883	8.001943

4
4403.2

8.020656	8.067869	8.083978	8.093065
8.010985	8.041014	8.073222	8.099716
8.001980	8.031029	8.054494	8.066897
8.009054	8.037575	8.068017	8.095027
8.008947	8.044025	8.077999	8.099716

-1

RECD1

16

111.[illegible]	1.[illegible]
157.[illegible]	.9[illegible]
1[illegible]9.274	.90[illegible]
1[illegible].744	.854
1[illegible]5.573	.825
208.574	.822
[illegible]21.214	.580
881.760	.575
910.032	.590
1013.264	.586
1098.564	.608
1230.071	.614
1324.061	.621
1745.123	.737
2125.732	.772
2452.161	.856

RECD2

13

72.060	1.274
133.366	.950
141.270	.919
149.408	.887
159.199	.866
512.852	.620
608.783	.611
714.754	.622
814.180	.629
1146.695	.684
1279.045	.715
1405.880	.738
1838.857	.876

RECD3

9

923.[illegible]	.[illegible]13
104[illegible].[illegible]	.[illegible]32
1[illegible]87.125	.[illegible]21
1[illegible].151	.515
13[illegible].5[illegible]	.520

RECD4

3

885.355	.563
[illegible]	[illegible]
1087.190	.573
1243.830	.586
1360.558	.598
1540.112	.629
1819.059	.709
1991.645	.752

RECD5

13

784.059	.658
827.388	.647
902.495	.651
957.124	.662
984.845	.663
1078.683	.685
1198.090	.697
1264.655	.716
1442.093	.758
1479.451	.781
1559.585	.785
1664.742	.814
1891.267	.877

RECD6

4

940.682	.663
1218.763	.716
1500.502	.770
1923.[illegible]	.903

RECD7

1

1258.082	.723

RECD8

4

856.318	.621
1276.702	.683
1607.340	.757
1928.995	.857

RECD9

4

885.493	.603
1313.942	.648
1751.413	.740
1993.411	.810

RECD10

4

900.721	.580
1343.509	.614
1809.938	.712
2043.935	.778

RECD11

4

895.637	.599
1206.871	.645
1764.224	.750
1991.837	.817

RECD12

4

879.410	.635
1258.458	.702
1674.793	.814
1905.906	.877

RECD13

4

953.837	.660
1255.188	.731
1680.653	.825
1906.136	.899

RECD14

4

868.754	.626
1269.308	.682
1721.823	.785
1932.293	.853

END

DATE
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